



Effect of corrosion on bond behaviors of rebar embedded in ultra-high toughness cementitious composite



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HIGHLIGHTS

- The rebar pre-corroded in a concrete environment was used in pull-out samples.
- A gentler post-peak behavior was obtained with increasing corrosion ratio.
- The effect of corrosion on bond strength was related with bond length.
- An empirical model was proposed to predict the bond strength.

ARTICLE INFO

Article history:

Received 23 August 2016

Received in revised form 11 January 2017

Accepted 2 February 2017

Keywords:

Corroded rebar

UHTCC

Bond

Slip

Strength

ABSTRACT

The bond between corroded rebar and ultra-high toughness cementitious composite (UHTCC) is a key factor in the mechanical properties of corroded reinforced concrete members repaired using UHTCC. This paper presents an experimental study on bond behaviors of UHTCC and corroded reinforcement obtained in a concrete environment through central pull-out tests. The experimental results revealed that all the UHTCC specimens failed in pull-out and that almost all showed an apparent average slip plateau. The post-peak bond behavior was improved with an increase in corrosion ratio. The change in bond strength with corrosion ratio is related to bond length. Bond toughness first rose and then decreased with corrosion ratio, but still remained close to that of non-corroded samples at about 15% of corrosion ratio. An empirical model was proposed to predict the bond strength between corroded rebar and UHTCC, and a good agreement was obtained.

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1. Introduction

Bonding between reinforcing bar and the surrounding concrete is fundamental for all reinforced concrete (RC) structures. For RC structures subjected to physical and chemical actions in an aggressive environment, bonding is greatly affected by reinforcement corrosion and concrete cracking caused by volume expansion of corrosion products [1,2]. For non-confined rebar, the bond strength first rises before cracking of the surrounding concrete and then degenerates with increasing corrosion ratio and crack width [3–5]. A moderate mass loss ratio (around 5.2%) of rebar can result in a reduction of about 78% in bond strength [3]. In addition, a study conducted by Yalciner [6] revealed that the effect of corrosion is more apparent for bonding with higher-strength concrete, showing greater degradation in bond strength and more brittle

bond-slip behavior. For confined rebar, a corrosion level of around 4% had almost no influence on bond strength, but substantial reduction took place for corrosion ratios up to about 6% [7]. Moreover, cyclic loading can aggravate the decrease in bond capacity for corrosion levels beyond around 5%, especially within the initial five cycles [8]. In addition, the use of reinforcing fibers can effectively delay corrosion cracking, limit crack development, and therefore improve bond strength at cracking and post-cracking stages [4,9].

More seriously, the load-carrying capacity of corroded RC members often decreases because of the reduction in bond capacity and cross-sectional area of the reinforcement [10–12]. Then the corroded RC members generally must be repaired to extend the service life of the whole structure. During repair, the cracked concrete and corrosion products attached to the reinforcement are usually first removed, and then the damaged members are further repaired using high-performance materials [13]. Therefore, the bond between corroded rebar and repair material is of great significance for the mechanical properties of the repaired RC members.

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Ultra-high toughness cementitious composite (UHTCC) [14] has a profound potential to serve as an effective repair material to improve the durability and service life of damaged structural members. Similarly to ECC (engineered cementitious composite) [15] and strain-hardening cement-based composite [16], UHTCC shows apparent tensile strain-hardening and stable multiple-cracking behaviors [14] as well as outstanding mechanical properties and fine durability [16–21]. Use of UHTCC as a repair layer for corroded RC beams delayed corrosion of the reinforcement and restored the initial load-carrying capacity even at high corrosion ratios, up to 10% [22]. Xu et al. [23] carried out a study on the corrosion behavior of RC/UHTCC composite beams with UHTCC cover in a tension zone. The experimental results revealed that UHTCC cover postponed corrosion development and corrosion cracking, thus ensuring a relatively high residual load-bearing capability.

However, a very limited number of studies have been performed on the effects of corrosion on the bond between repair materials and the rebar from which corrosion products were cleaned. Lack of bond test data between corroded rebar and UHTCC may lead to a conservative design for repair of corroded RC structures using UHTCC. In this paper, the bonding between UHTCC and pre-corroded rebar in a concrete environment is investigated to simulate the actual retrofit condition. Failure modes, bond-slip behaviors, bond strength, and bond toughness are compared with respect to corrosion ratio and bond length. The experimental results can provide a significant reference for repair of corroded RC members using UHTCC.

2. Experimental program

2.1. Pre-corrosion of rebar

To simulate corrosion conditions in practical engineering, the rebar used for the pullout specimens was first pre-corroded. A total of 27 rebar specimens with a length of 400 mm were pre-corroded in concrete specimens. The target corrosion ratios were designated as 5%, 10%, and 15%. These 27 steel bars were divided into three groups with nine steel bars, with each group corresponding to a target corrosion ratio. HRB400 deformed rebar with a diameter of 16 mm was used. The pre-corroded rebar was offset in a concrete cylinder with a cover thickness of 25 mm. Fig. 1 shows the detailed configuration of the pre-corroded specimens. The accelerated pre-corrosion was conducted using applied direct current. Fig. 2 shows the corrosion test setup. As shown in Fig. 2, the cylinder specimens were placed into the 3.5% NaCl solution, and the rebar was connected with the power anode and the stainless rebar with the power cathode. A constant current was applied with a corrosion current density of $300 \mu\text{A}/\text{cm}^2$. Based on Faraday's law, the corrosion age can be approximately calculated using Eq. (1):

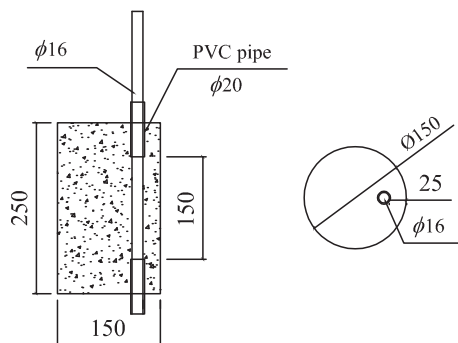


Fig. 1. Details of concrete specimen for pre-corrosion.

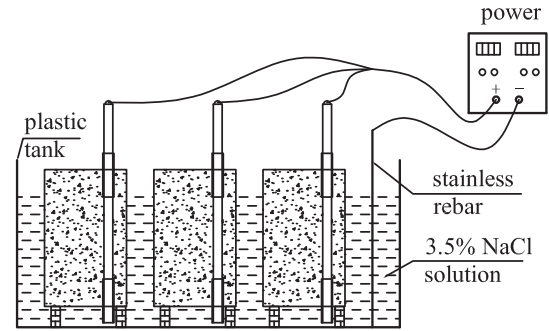


Fig. 2. Test set-up for accelerated corrosion of rebar.

$$t = \frac{zN\Delta m}{MI}, \quad (1)$$

where Δm is the mass loss of corroded reinforcement (g), N is Faraday's constant ($6.02 \times 10^{23} \text{ mol}^{-1}$), and z is the ionic charge number ($z = 2$) of iron. M is the molar mass of iron (56 g/mol), and I is the corrosion current intensity (A), which can be obtained by Eq. (2):

$$I = iS, \quad (2)$$

where i is the corrosion current density and S is the superficial area of reinforcement within the corrosion region. After pre-corrosion was complete, the corroded rebar was taken out by splitting the concrete cylinder. Similarly to the retrofit of corroded members in practice, the corrosion products and the concrete bonded onto the rebar were cleaned up using a wire brush.

2.2. Specimens for pull-out test

A total of 45 pull-out specimens, which were divided into 15 groups with three specimens in each group, were tested. These specimens included nine groups of UHTCC specimens with corroded reinforcement, three groups of UHTCC specimens with non-corroded reinforcement, and three groups of concrete counterparts with non-corroded reinforcement. A 150-mm cube was used as the central pull-out specimen, with reinforcement centrally placed in the specimen. Fig. 3 shows details of the pull-out specimen.

The variable parameters were corrosion ratio and bond length. The corrosion ratios included 0% and the target pre-corrosion ratios of 5%, 10%, and 15%. Note that the actual corrosion ratio calculated based on the mass loss method after pull-out tests may be different from the target corrosion ratio. The bond length, (l_b), was designated as 3, 5, and 7d, corresponding to 48, 80, and 112 mm respectively. To ensure the target bond length, a pair of PVC pipes was fixed onto the two ends of the rebar in contact with the specimen matrix. Furthermore, the gap between the rebar and the PVC pipe was sealed using glass glue to prevent penetration of cement paste.

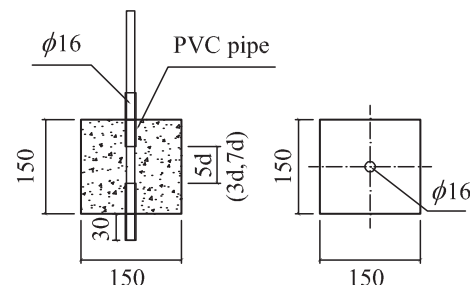


Fig. 3. Details of pull-out test specimen.

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